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THE RELATIVE LOUDNESS OF PURE AND COMPLEX TONES*

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ABSTRACT

THE RELATIVE LOUDNESS OF PURE AND COMPLEX TONES

OBJECT

To investigate the relative loudness of pure and complex tones and to describe a method of harmonic analysis of complex tones.

RESULTS AND CONCLUSIONS

Utilizing the method of adjustment, subjects equated the loudness of a variable intensity pure tone (sine wave) with a reference standard complex tone (square wave). A loudness match was obtained at 100, 150, 200, 300, 400, 700, 1000, 2,000, and 4,000 cps. A harmonic analysis of complex wave form was obtained by photographing the cathode ray tube of a panoramic sonic analyser and measuring the relative intensities of the fundamental and harmonics of the complex wave form on the print.

The absolute intensity of the pure tone was considerably greater at the lower frequencies when matched for equal loudness with the complex tone. At 100 cps the difference between the pure and complex tone, relative to the loudness of the pure tone, could be obtained by converting the harmonic components of the complex tone to units of equal loudness or sones, and performing a simple summation.

RECOMMENDATIONS

Considerable power savings may be realized if complex tones are used in preference to pure tones in auditory displays where low frequency signals are encountered. An investigation of the feasibility of utilizing other complex tones in auditory displays is desirable.

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THE RELATIVE LOUDNESS OF PURE AND COMPLEX TONES

I. INTRODUCTION

A statement common in psychological literature is that complex tones sound louder than pure tones of equal frequency and absolute intensity. Experiments with acoustically complex tones have shown that if its components are sufficiently separated from one another along the frequency scale, the total loudness is equal to the sum of the loudnesses of the individual components presented separately (1, 2, 3, 4, 5). If the frequency components of the complex tones are not widely separated, however, masking and interference effects occur and the total loudness is usually somewhat less than the sum of the individual loudnesses, by a quantity which usually must be determined empirically. Because of this difficulty, experiments dealing with the relative loudness of complex tones generally use tones in which the harmonic components are of similar strength and widely separated in the frequency spectrum (1). Little consideration is given to complex tones of the type normally encountered, tones in which the frequency components are of unequal strength and which are close enough to overlap on the cochlea. In this experiment, the relative loudness of such a complex tone, a square wave, is determined by comparing it with a pure tone at the same frequency.

II. EXPERIMENTAL

A. Apparatus

1. Krohn-hite pushbutton oscillator: an audio oscillator capable of generating sine and square waves from .01 to 99,999.9 cps.

2. Permoflux PDR-8 earphones: matched and calibrated.

3. General Radio decade attenuator.

4. Kellogg condenser microphone, preamplifier, and cathode follower: factory calibrated for use with a 6-cc coupler for determining absolute sound pressures from earphones.

5. Panoramic Sonic Analyzer, PR-1, and signal alternator: a device which sweeps the audio spectrum from 40 to 20,000 cps, permitting almost immediate graphic analysis of any complex wave form on the face of a cathode ray tube.

6. Sound treated room: approximately 10 x 12 x 8 feet, acoustically and electrically shielded.

7. Ballentine AC voltmeter:

The bulk of this equipment was used in the calibration of the earphone. The technique is described in Section C - Method, and the apparatus line-up is shown in Figure 1.

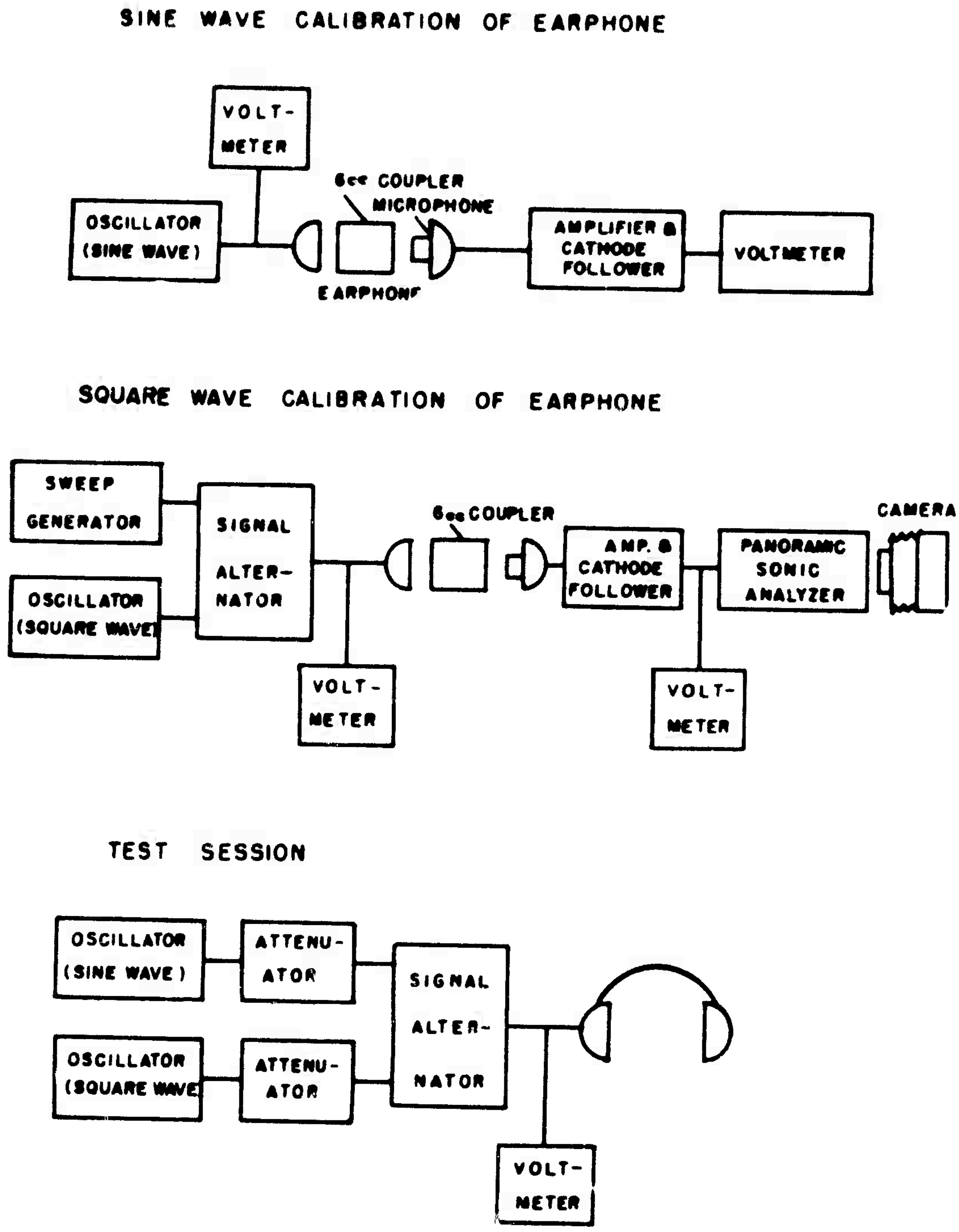

Fig. 1. Block diagrams of apparatus.

B. Subjects

Sixteen subjects, selected from the staff of the Laboratory, were used. Audiograms had been obtained on the subjects and all had normal hearing.

C. Method

1. Calibration - Exact calibration of all apparatus used for both sine waves and square waves was essential to facilitate comparison between the two wave forms. A Kellogg condenser microphone with associated cathode follower was used to calibrate the Permoflux PDR-8 earphones. A constant voltage audio frequency input fed into the earphone was compared with the voltage output of the microphone when the earphone and microphone were mounted in a 6 cc coupler. Input voltages of .1, .2, .3, and .4 volts were used. The earphone characteristics remained substantially the same at all voltages. All voltages, both earphone input and microphone output voltages were measured with a Ballentine AC voltmeter. Calibration at .4 volts for the Permoflux PDR-8 earphones used in this experiment is given in Table 1.

TABLE 1

CALIBRATION OF PERMOFLUX PDR-8 EARPHONES

0.4 Volt Input

Frequency		Microphone output voltage*
100 cps**		1.4×10^{-2}
200 cps**		2.2×10^{-2}
300 cps**		2.55×10^{-2}
400 cps**		2.75×10^{-2}
500 cps		2.8×10^{-2}
600 cps		2.8×10^{-2}
700 cps**		2.8×10^{-2}
800 cps		2.82×10^{-2}
900 cps		2.78×10^{-2}
1000 cps**		2.78×10^{-2}
2000 cps**		2.2×10^{-2}
3000 cps		3.37×10^{-2}
4000 cps**		1.75×10^{-2}
5000 cps		1.77×10^{-2}
6000 cps		2.2×10^{-2}
7000 cps		1.3×10^{-2}
8000 cps	less than	1.0×10^{-2}
9000 cps	less than	1.0×10^{-2}
10000 cps	less than	1.0×10^{-2}

*Kellogg condenser microphone - 2.8×10^{-3} volts corresponds to a sound pressure level of 80 db. relative to 2×10^{-4} dynes/cm^2.

**These frequencies were used in the test session.

For square wave calibration the same apparatus: audio oscillator, earphone, 6-cc coupler, and microphone, was used; but the output of the microphone was fed into the Panoramic Sonic Analyzer (PSA). This analyzer had previously been carefully calibrated by using known audio frequency inputs with exact measured voltages. The audio oscillator was set to produce a square wave of a given fundamental frequency. In addition, the internal sweep circuit of the PSA produced an audio frequency of from 40 to 20,000 cps. Both the square wave and the audio frequency sweep were fed into an alternating switch, which presented alternately each signal to the PSA. By adjusting the gain of the audio frequency sweep, it was possible to get a graphic representation of the characteristic curve of each earphone. The harmonic components of the square wave were superimposed on this characteristic curve and a photograph was made of each frequency. All input and output voltages were measured with a Ballentine AC voltmeter. Figure 1 shows a block diagram of the circuitry used. Figures 2 through 1' are photographs of the face of the cathode ray indicator of the PSA.

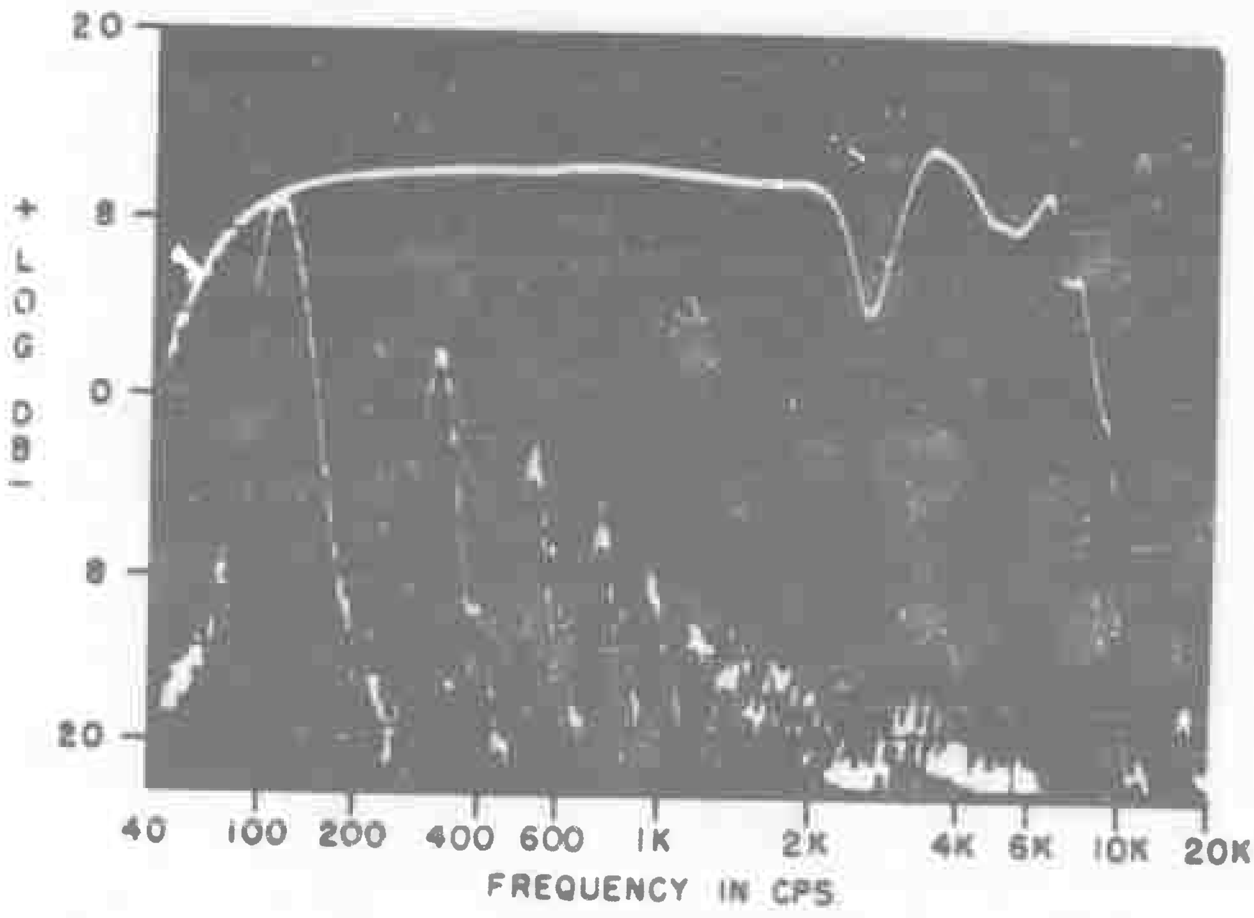

Fig. 2. Square wave, 100 cps earphone input .705 V. Microphone output .0265 V.

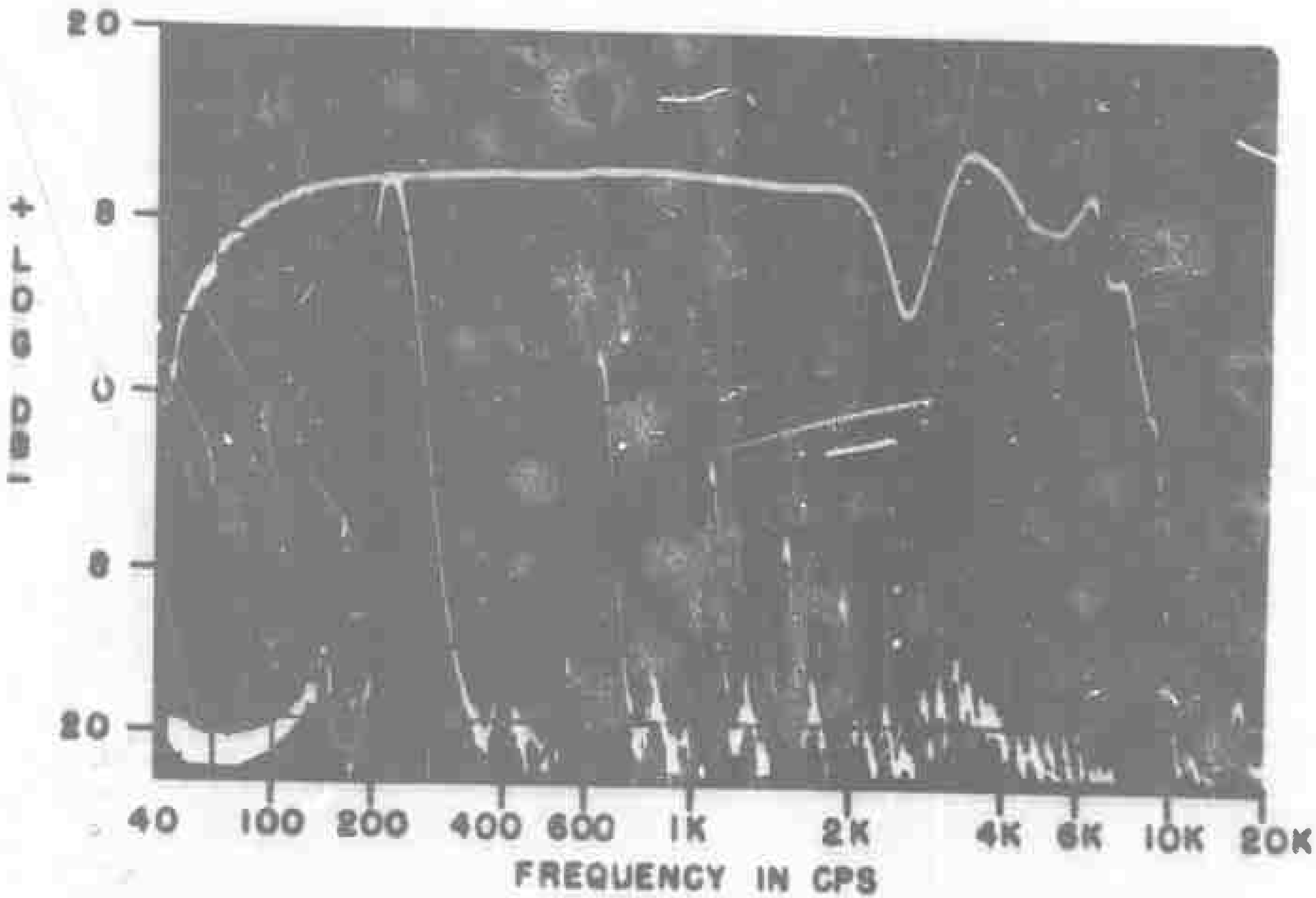

Fig. 3. Square wave, 200 cps - earphone input .76 V - Microphone output .036 V.

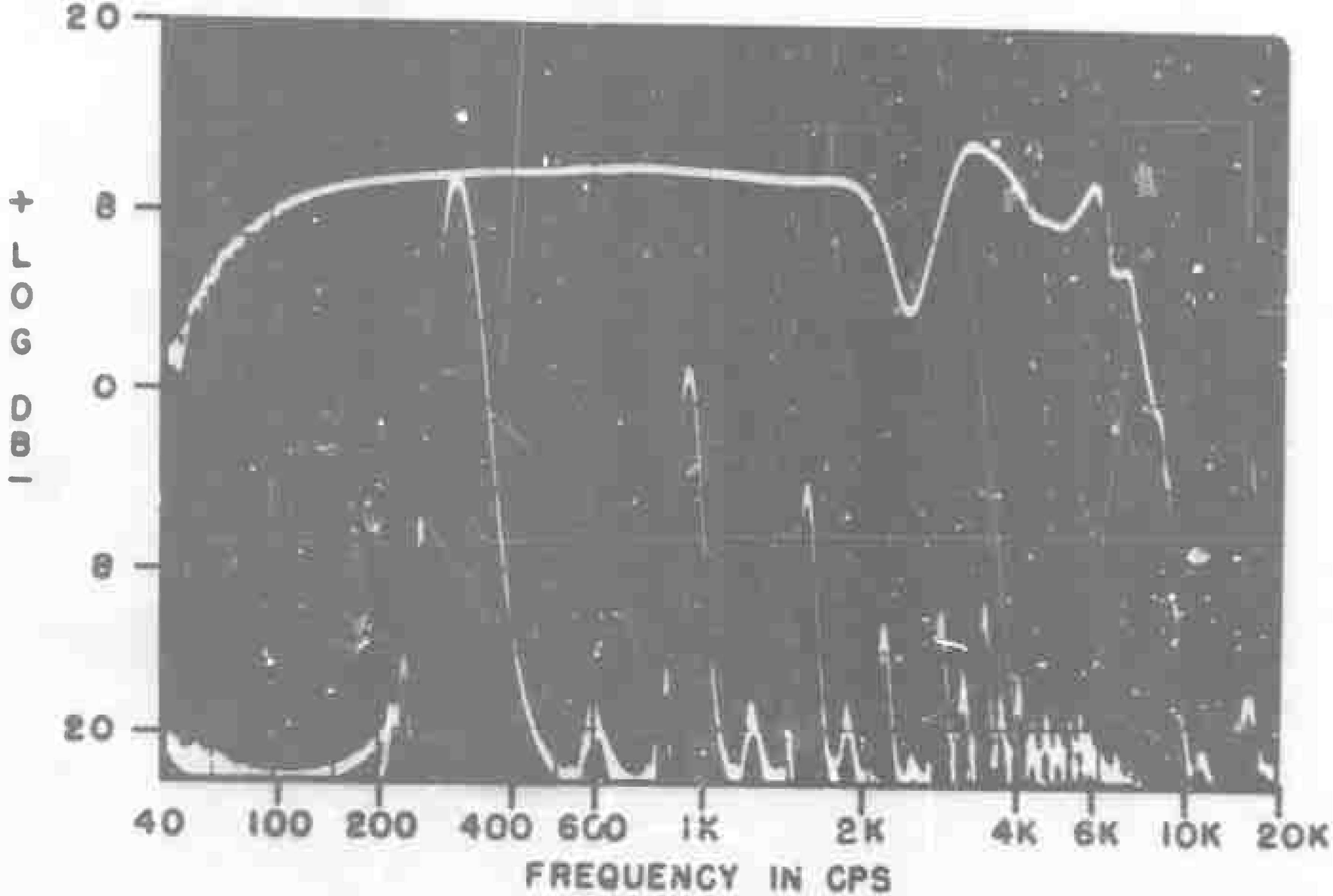

Fig 4. Square wave, 300 cps - earphone input .75 V - Microphone output .0405 V.

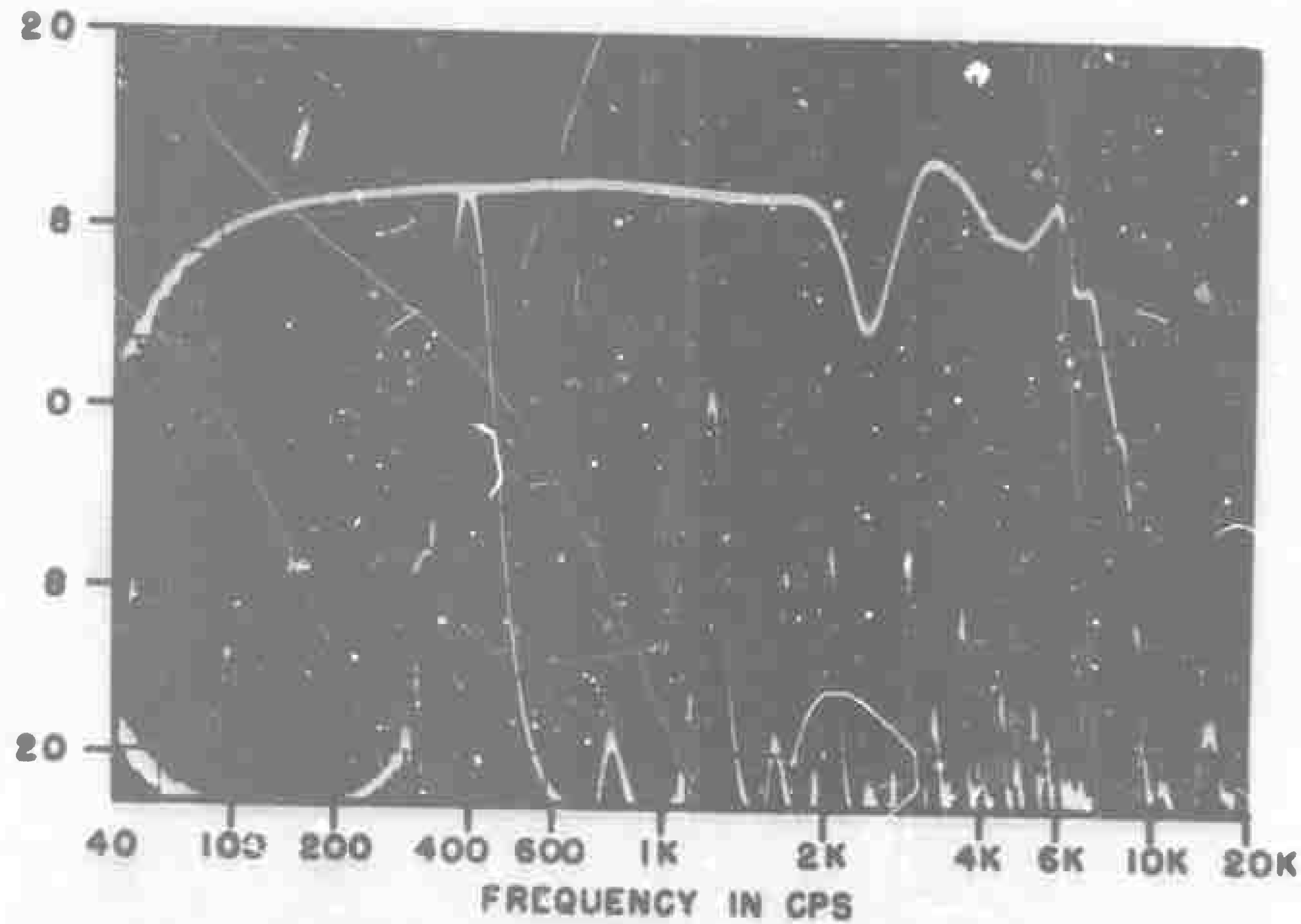

Fig. 5. Square wave, 400 cps - earphone input .78 V - Microphone output .045 V.

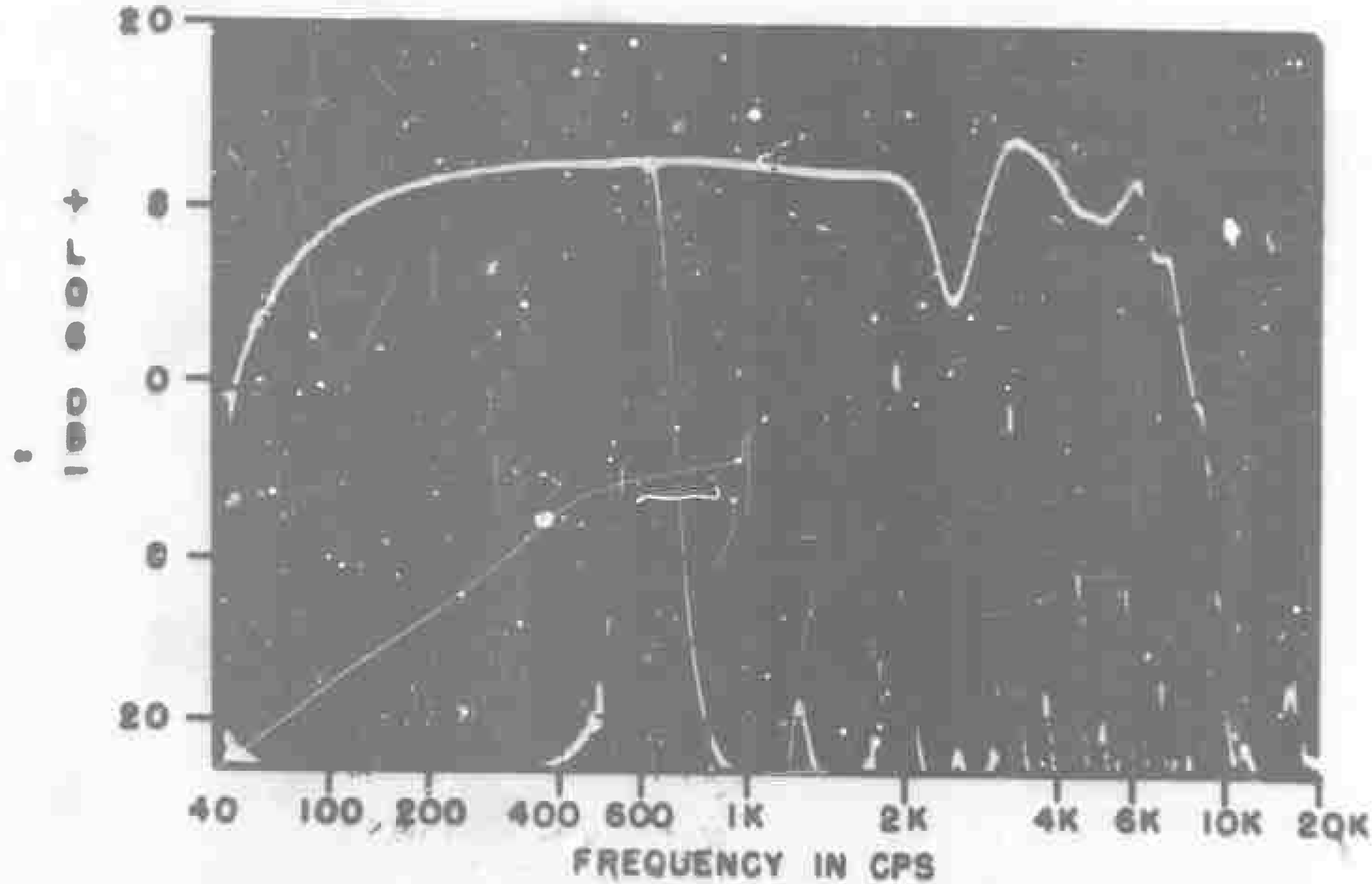

Fig. 6. Square wave, 600 cps - earphone input .81 V - Microphone output .048 V.

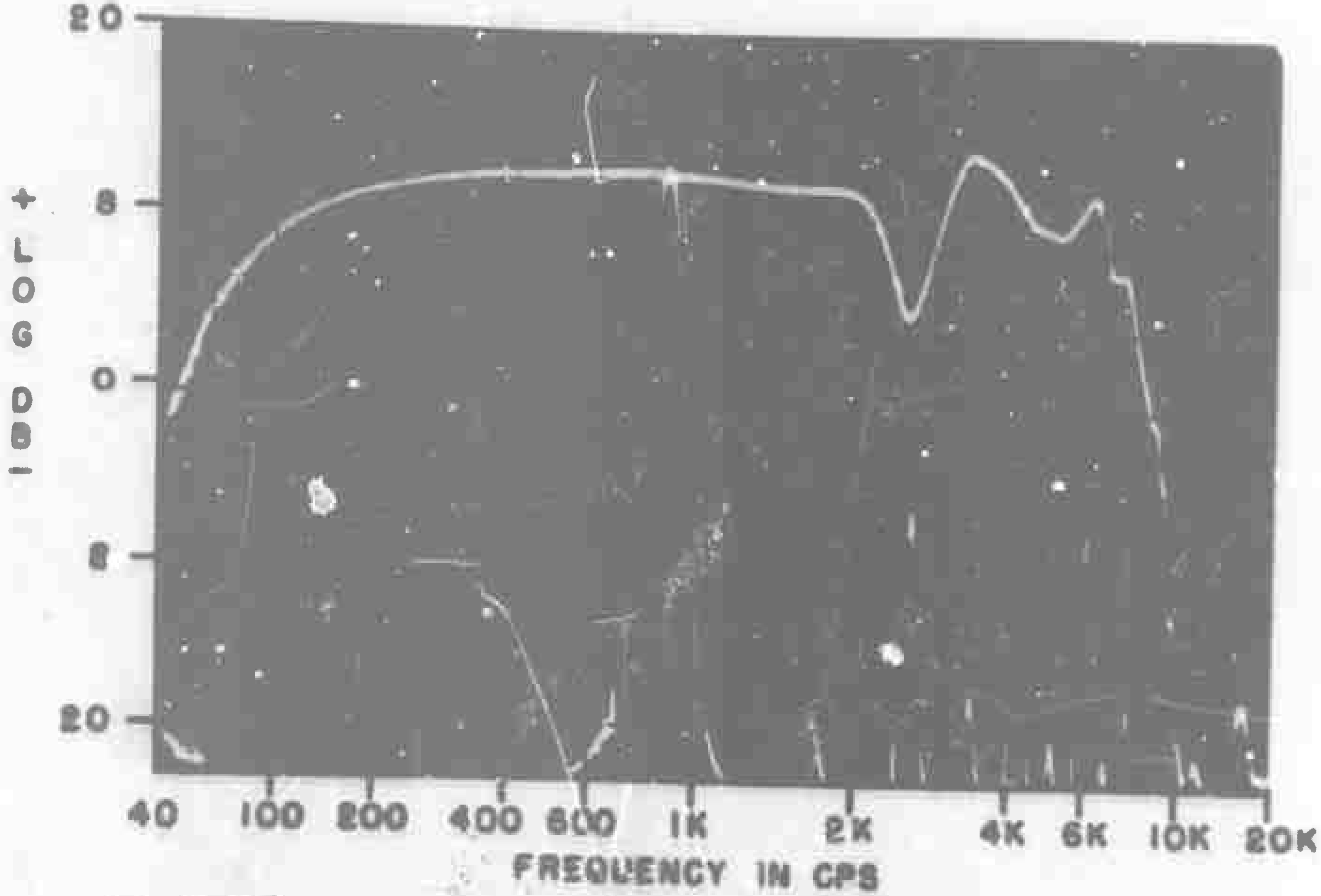

Fig. 7. Square wave, 800 cps - earphone input .83 V - Microphone output .0465 V.

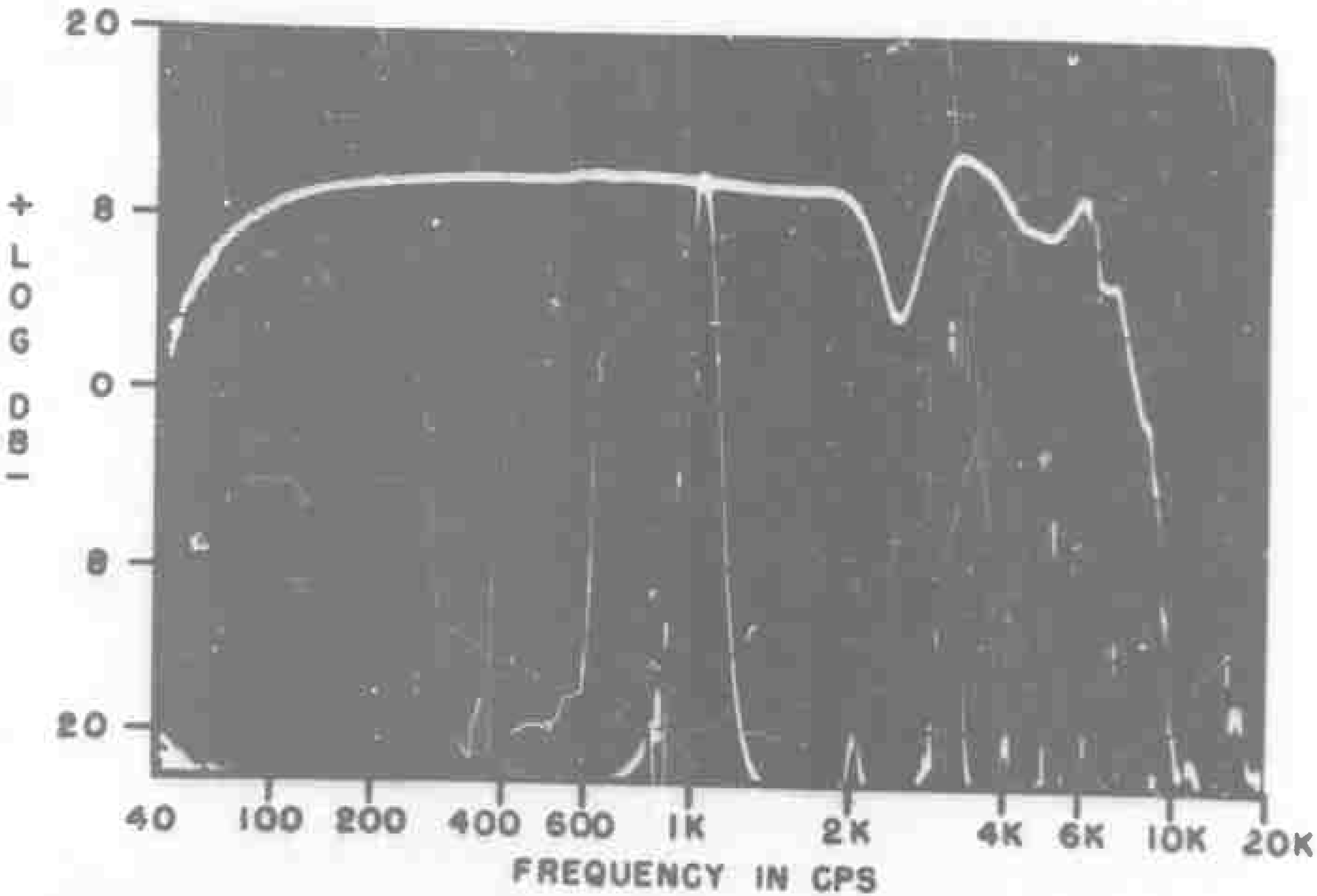

Fig. 8. Square wave, 1000 cps - earphone input .87 V - Microphone output .0485 V.

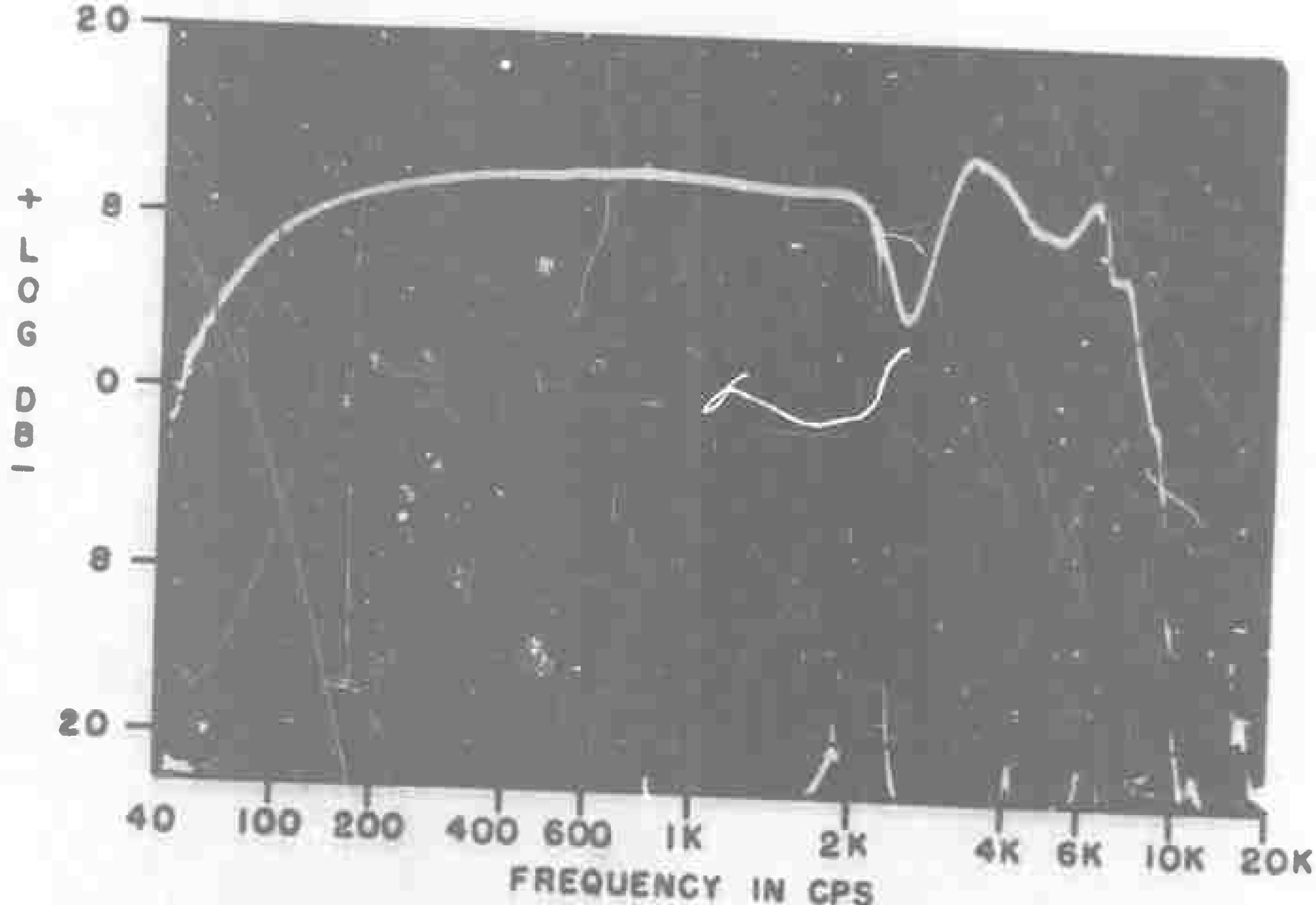

Fig. 9. Square wave, 2000 cps - earphone input .82 V - Microphone output .0365 V.

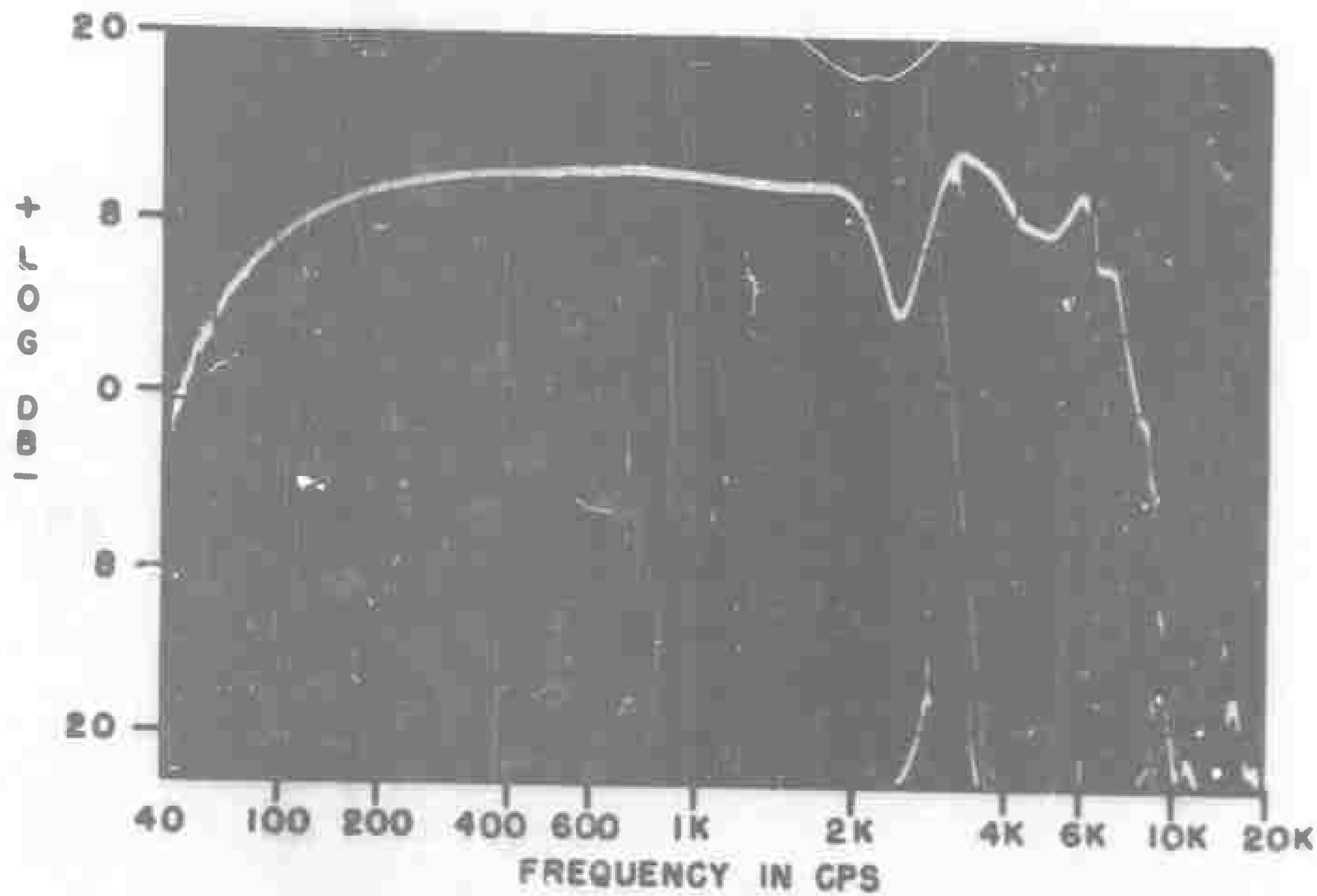

Fig. 10. Square wave, 3000 cps - earphone input .79 V - microphone output .046 V.

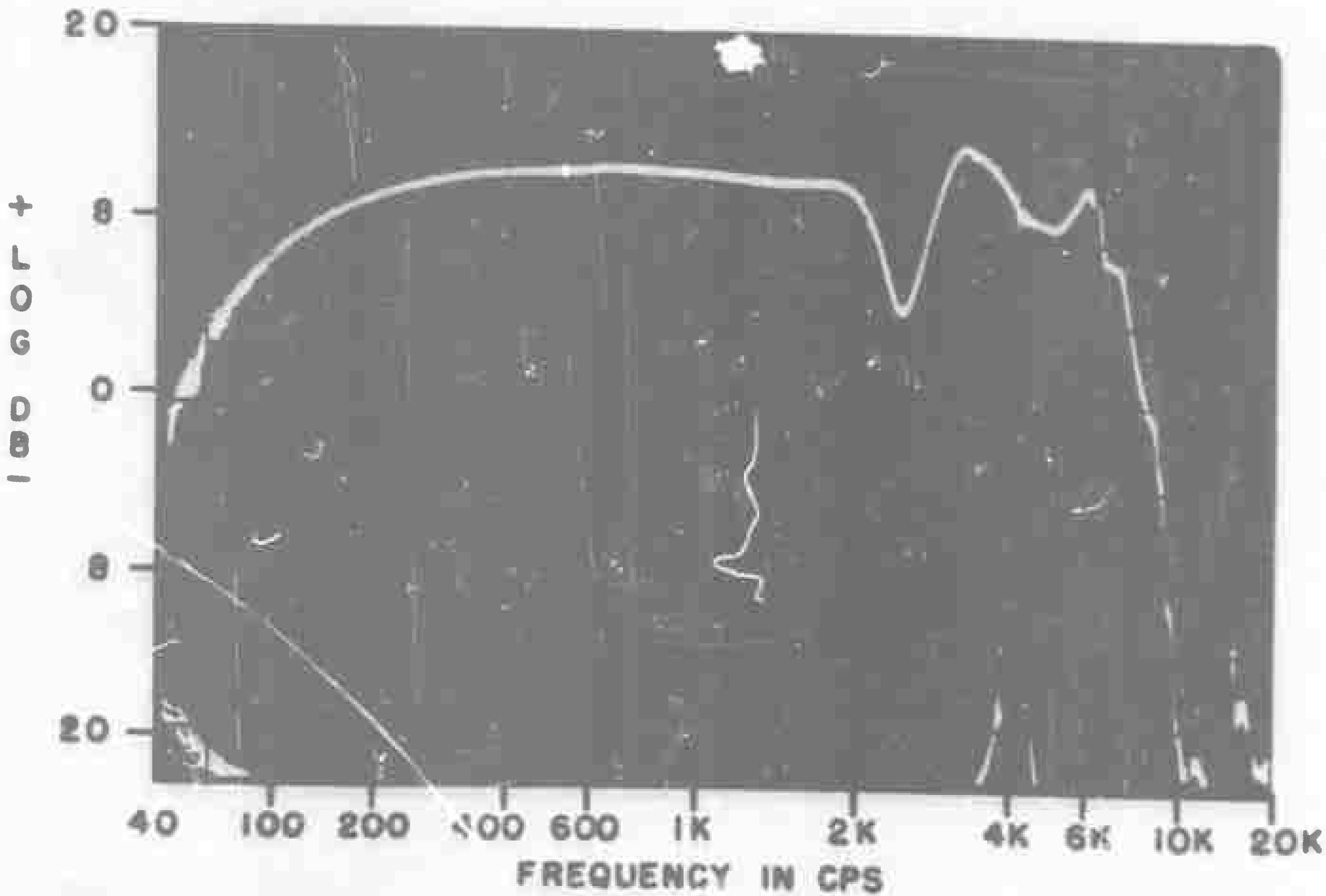

Fig. 11. Square wave, 4000 cps - earphone input .79 V - microphone output .0315 V.

By measuring the traces in the photographs, the actual strengths of the fundamental and harmonic components of the square waves could be determined. Table 2 gives the magnitude of fundamentals and harmonics of the square waves in decibels. It will be noticed that fewer harmonics appear at higher frequencies due to the fall off in the high frequency response of the PDR-8 earphone.

TABLE 2

MAGNITUDE OF FUNDAMENTALS AND HARMONICS OF SQUARE WAVES IN DECIBELS*

		Harmonics						
Frequency	Fundamental	3	5	7	9	11	13	15
100 cps**	92	84	79	75	72	70	68	66
200 cps**	94	84	77	73	70	64	67	--
300 cps**	93	83	76	68	69	70	65	--
400 cps**	94	83	74	74	71	66	65	--
600 cps	94	83	81	71	70	65	--	--
800 cps	94	75	75	73	64	--	--	--
1000 cps**	94	86	74	68	--	--	--	--
2000 cps**	92	81	--	--	--	--	--	--
3000 cps	95	64	--	--	--	--	--	--
4000 cps**	93	--	--	--	--	--	--	--

*relative to .0002 dynes/cm^2
**These frequencies were used in the test session.

2. Experiment

The experimental procedure was relatively simple. A sine wave and square wave in the same fundamental frequency were fed into the signal alternator. A subject, wearing a pair of PDR-8 earphones, heard each signal alternately at 1-second intervals. The square wave was fed into the earphones at a constant voltage of .3 volts. The sine wave signal could be varied by means of an amplifier gain control, from 0 volts to 10 volts. The subject's task was to adjust the intensity of the sine wave until the sine wave signal and the square wave signal appeared to be of equal loudness. Subjects were asked to equate tones only for loudness and not for relative annoyance or other extraneous characteristics. Two upward and two downward matches were made for each frequency used in the experiment. Voltages, recorded on a Ballentine AC voltmeter, were monitered for both the sine wave signal and the square wave signal. Each experimental session took about 45 minutes. The frequencies used in this experiment were 100, 150, 200, 300, 400, 700, 1,000, 2,000, and 4,000 cps. A random order of presentation was used.

III. RESULTS AND DISCUSSION

Several curves were drawn based on the difference between the mean of the pure tone voltage and the mean of the complex tone voltage at each frequency used in the experimental session. The power ratio curve on Figure 12 shows the ratio of pure tone to complex tone electrical power necessary to produce tones of equal relative loudness. The electrical db curve on the same figure restates the information given in the power ratio curve in terms of decibels difference between the two tones (5).

Since the earphones did not produce the same acoustic output for a given electrical input at all frequencies, a correction procedure, based on the earphone calibration characteristics given in Table 1, and the measurements made on Figures 2 through 11, was used to translate the voltage difference figures into sound pressure differences. The procedure consisted of determining the relative efficiency of the earphone at each frequency by determining the ratio of electrical input to acoustic output using the data from Table 1, and using this efficiency factor to derive a sound pressure for the voltages obtained at that frequency in the test session. The acoustic db curve in Figure 12, showing the difference in sound pressure between pure and complex tones of equated loudness, was derived by this method. The relationship of these curves to the electrical energy input is given in Table 3.

TABLE 3

COMPARISON OF PURE TONES (SINE WAVE) AND COMPLEX TONES (SQUARE WAVE) MATCHED FOR EQUAL LOUDNESS

Frequency	Sq. wave voltage (R.M.S.)	Voltage ratio*	Power ratio	Decibels difference (sine-square wave) Electrical	Acoustic
100 cps	2.04 v.	6.8	46.5	16.6	16.2
150 cps	1.22 v.	4.08	16.7	12.05	12.6
200 cps	.78 v.	2.6	6.8	8.3	9.8
300 cps	.465 v.	1.55	2.4	3.8	5.8
400 cps	.46 v.	1.53	2.35	3.7	5.4
700 cps	.38 v.	1.27	1.62	2.1	3.6
1000 cps	.36 v.	1.2	1.44	1.6	3.2
2000 cps	.34 v.	1.13	1.28	1.06	3.2
4000 cps	.293 v.	.98	.96	-.2	.6

*Referred to a constant square wave voltage of .3 v.

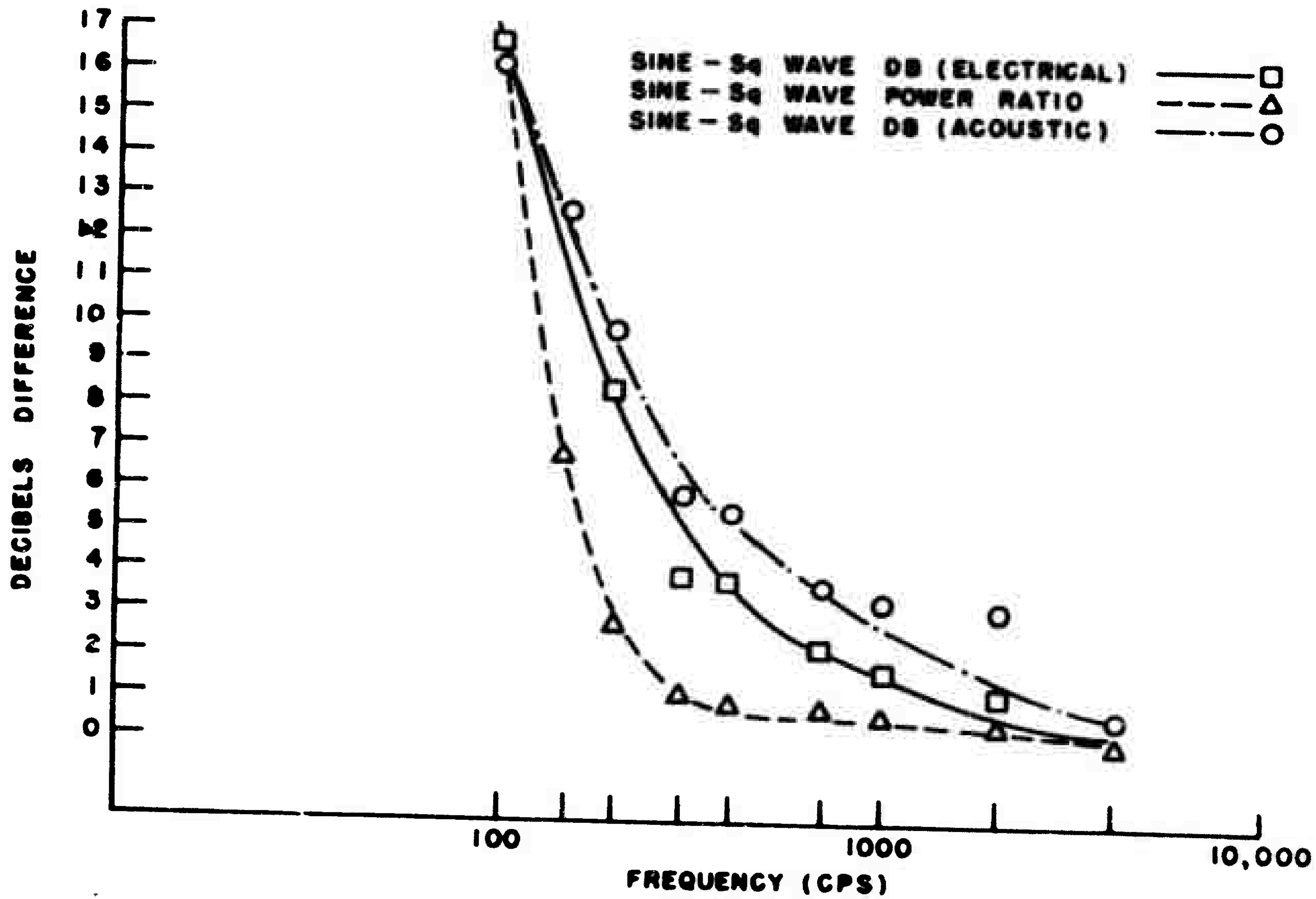

Fig. 12. Difference in power ratio and decibels of sine and square wave tones of equal loudness.

All three curves point to the conclusion that, at low frequencies, complex tones sound considerably louder than pure tones of the same sound pressure level, and that the relative loudness function changes smoothly with changes in fundamental frequency of the tones. The great disparity between the two tones at the lower frequencies is due to the fact that the human ear is markedly less sensitive to pure tones around 100 cycles than to pure tones higher in the frequency spectrum.

It should be noted that at the higher frequencies, where the number of over-tones is smaller, the difference becomes negligible. Figure 11 indicates that at 4,000 cps there is almost no energy in the harmonics of a square wave with the equipment used in this experiment. Consequently, both the pure tone and complex tones should sound equally loud, with equal energy input. In making the comparison, subjects often remarked that they could not tell the two tones apart in the upper frequency ranges. The slight discrepancies between the curves for acoustic db and electric db can be traced to the presence of resonant points in the characteristic curve of the earphones. In general, both curves agreed quite closely, with the earphones appearing to be more efficient in translating electrical energy into acoustic power in the middle frequency ranges.

In an effort to test the hypothesis that the loudness of a complex tone can be predicted by summing the loudnesses of all the component tones, the harmonic constituents of the square wave forms, shown in Table 2, were converted into units of relative loudness, or sones, as shown in Table 4. This conversion was made by the use of an equal loudness contour chart given in Stevens and Davis (3).

TABLE 4

LOUDNESS IN SONES OF SINE WAVES AND SQUARE WAVES

Frequency	Sine Waves		Square Waves**		Difference^x	
	DB	Sones	DB	Sones	DB	Sones
100 cps	108	91	91.8	100	16.2	-9
150 cps	105.8	82	93.2	--*	12.6	--*
200 cps	103.8	78	94	98	9.8	-20
300 cps	101	66	95.2	90	5.8	-24
400 cps	101.2	63	95.8	95	5.4	-32
700 cps	99.4	57	95.8	--*	3.6	--*
1000 cps	99	55	95.8	71	3.2	-16
2000 cps	96.4	44	93.2	45	3.2	-1
4000 cps	93.2	30	92.6	30	.6	0.00

*photographic data not available
**Sum of fundamentals and harmonics
^xSine wave minus square wave values

The loudnesses of the harmonics of the complex tone were summed (Table 4), but for two of the tones, 150 cps and 700 cps, photographic data were not available. Consequently, these tones were not included in the analysis. The loudness in sones for both the pure tone and the complex tone, for each frequency, was plotted as shown in Figure 13. The difference between the curves is shown in Figure 14. The greatest difference between these curves of 32 sones occurs at approximately 400 cps.

Since the sone scale is a linear scale of loudness, and the tones used have loudnesses of about 100 sones, the maximum error using the harmonic summation method in computing the relative loudness of the tones used in this experiment is about 31%.

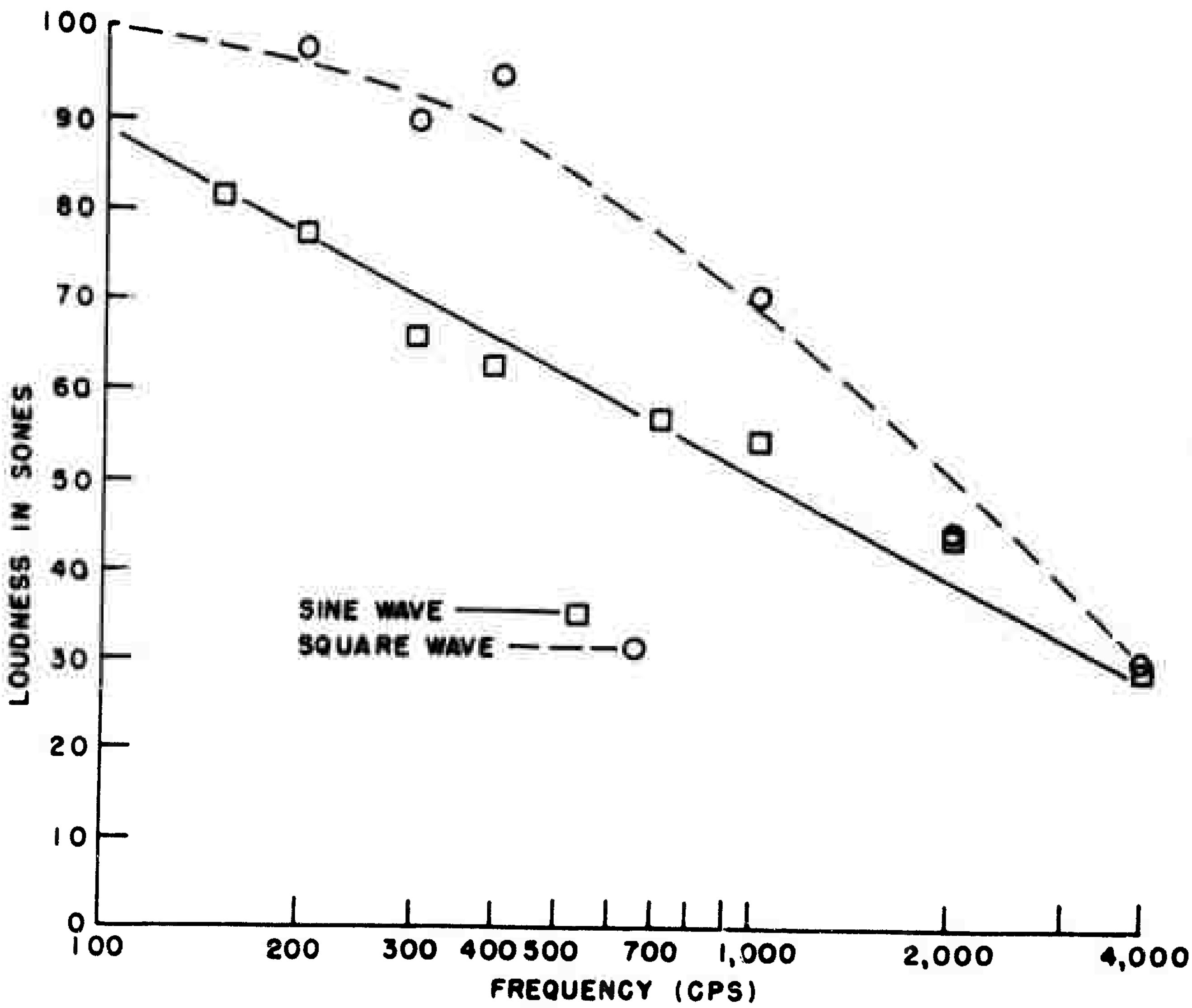

Fig. 13. Calculated loudness in sones of sine and square wave tones.

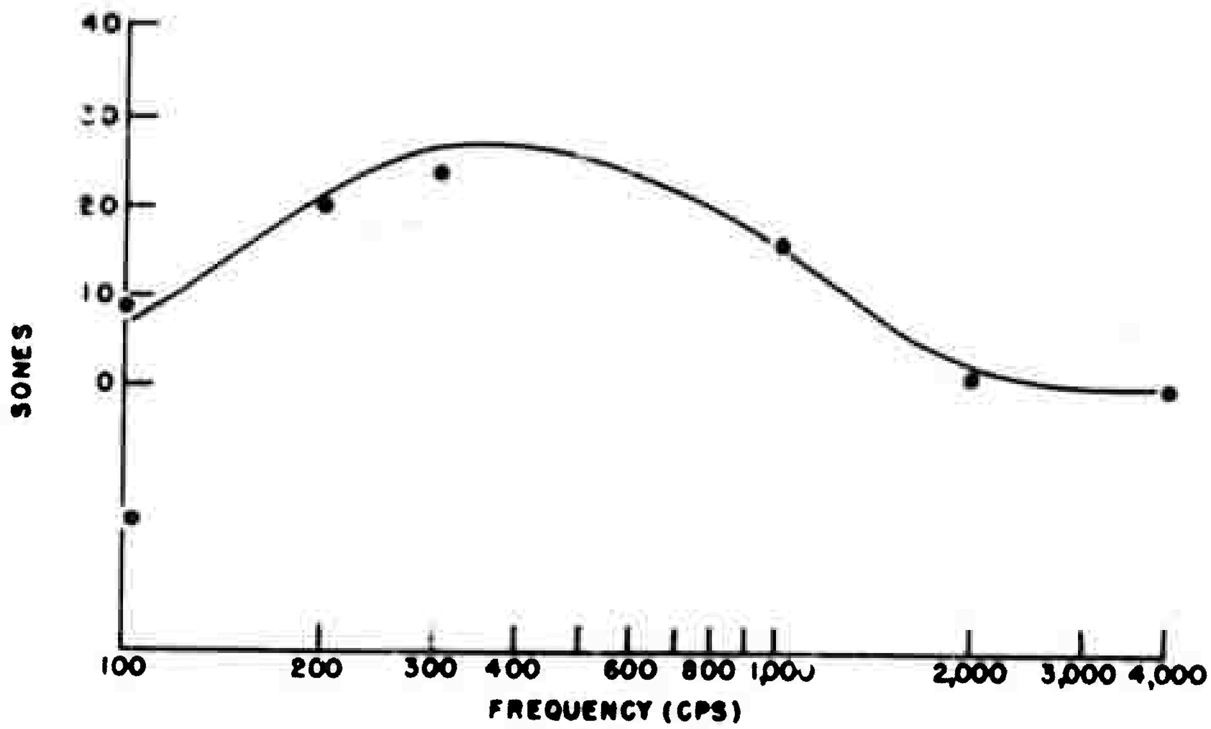

Fig. 14. Difference in sones between sine and square wave tones of equal loudness.

A possible explanation for the fact that the curve for the pure tone on the sone scale lies somewhat below that of the complex tone in Figure 13 may be due to the method of using the pure tone as the variable stimulus and not the complex tone. It appears to be the general rule that subjects overestimate an intense variable relative to an intense standard and underestimate a weak variable relative to a weak standard. Consistent with this general rule, the subject tends to undershoot when he adjusts the stimulus to be equal to an intense standard, and he tends to overshoot when the standard is weak. For example, in the extreme case, when the standard borders on the painful, the subject does not err in the direction of setting the variable too high. The optimum intensity for minimization of this type of bias appears to be about 70 db (4). In this experiment the majority of the tones used were over 90 db.

Two alternative explanations can be hypothesized. One is that the sone scale is not entirely adequate for use with the summation technique. Stevens indicates that a good deal of research must be carried out on this type of subjective loudness scale before really high levels of reliability and accuracy can be obtained. The other explanation is the possible presence of masking and interference phenomena which may tend to make the complex tones, especially those in the middle frequency ranges, seem less loud than the individual loudnesses of their harmonic components would indicate. The failure of simple additivity may be due to the fact that the neural activities set up by the several components on the cochlea overlapped.

Stevens gives an empirical formula for determining the loudness of a continuous noise (4). This rule says that for all levels above about 50 db the loudness L changes by a factor of 2 when the overall sound pressure level, N, changes by 10 db. The formula is $\text{Log } L = 0.03N - S$ where S is the spectrum parameter. From the data in the present study, we have not succeeded in working out a method of evaluating S from the square wave harmonic analysis that produces significantly better results than simply adding sones.

IV. RECOMMENDATIONS

An investigation into the relative loudness characteristics of other wave forms is suggested. Pulses of known repetition rate and pulse width, clipped sine waves, and artifically constructed wave forms of known harmonic component should be investigated. From an analysis of these wave forms it should be possible to compute an empirical formula which gives the relative loudness of any wave form of known harmonic construction. The techniques presented in this experiment permit an adequate analysis of harmonic strength.

The practical use of relative loudness information is immediately apparent. It should be possible to design auditory displays which sound as loud as pure tone displays but require significantly less power.

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